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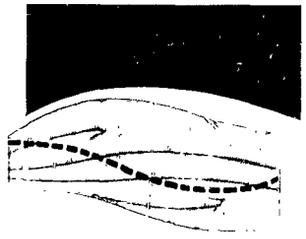

RELATIONSHIPS BETWEEN TROPICAL PRECIPITATION AND KINEMATIC CLOUD MODELS

REPORT NO. 1

Contract No. DA - 36-039 SC 89099

DA Project No. 3A 99-27-005

First Quarterly Progress Report

1 May 1962 - 31 July 1962

Sponsored by U.S. Army Signal Research and Development Laboratory

Fort Monmouth, New Jersey

THE TRAVELERS RESEARCH CENTER INC.

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OBJECT

The object of this research is to study relationships between tropical precipitation and the associated circulations of water vapor and condensate.

Prepared by: Edwin Kessler, III
Edward A. Newburg

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1.0 FACTUAL DATA

1.1 Introduction

The study supported by Contract DA 36-039 SC 89099 is intended to illuminate the relationships between tropical circulations and their associated distributions of water vapor and condensate. A reasonably complete description of these relationships must consider macro- and mesoscale thermodynamic influences as well as cloud physics processes and the kinematic relationships between wind and water distributions.

Although there has been substantial progress in each of these problem areas, their synthesis has been considered only slightly. The present effort under this contract is directed toward a description of the role of cloud physics processes, combined with modeled tropical circulations, vapor distributions, and condensation functions, in affecting the distributions of precipitation, cloud, and vapor.

1.2 Collection of Unpublished Results

This contract has enabled us to finish certain investigations that have been in progress for the past two years and to prepare the findings for publication. The typed manuscript was submitted to the Monthly Weather Review on July 31, 1962. Since most of the results discussed in this article were not developed under this contract, we are planning not to print it as a scientific report under this contract. The abstract is given below.

ELEMENTARY THEORY OF ASSOCIATIONS
BETWEEN ATMOSPHERIC MOTIONS
AND DISTRIBUTIONS OF WATER CONTENT

by

Edwin Kessler, III

ABSTRACT

This article discusses some of the kinematic relationships between distributions of precipitation and air motions, based on analyses of continuity equations embodying the principal assumptions that (1) water vapor shares the motion of the air in all respects and (2) condensate shares

horizontal air motion, but falls relative to air at a speed that is the same for all the particles comprising precipitation at a particular time and height. Among topics considered are the steady-state precipitation rate in a saturated horizontally uniform updraft column; the relationship $N(V + w) = \text{constant}$, where N is the number of uniform particles comprising precipitation at a particular point in space and time, V is their fall speed, and w is the updraft; a closed formulation for the particle concentration and size in precipitation that is composed of particles of the same size at any point in space and time; a comparison of no evaporation and instantaneous evaporation of condensate in two two-dimensional model wind fields; and kinematic descriptions of the radar-observed generators and stalactites.

1.3 Formal Development of Solutions of the One-dimensional Continuity Equation

The two premises noted in the abstract above are implicit in this continuity equation for water substance:

$$\frac{\partial M}{\partial t} = - u \frac{\partial M}{\partial x} - v \frac{\partial M}{\partial y} - (w + V) \frac{\partial M}{\partial z} - M \frac{\partial V}{\partial z} + wG, \qquad (1)$$

where M is the density of water substance in all its phases minus the saturation vapor density; $G = -dQ_s/dz$, where Q_s is the saturation vapor density; V is the fall speed relative to the air of M when M is positive; and V is zero when M is negative. The other terms have their usual meanings.

In references [3] and [4], solutions of the one-dimensional form of Eq. (1) for an incompressible atmosphere and constant fall speed of condensate are given for the limits $0 \leq z \leq H$ for the case in which $w = (4w_{max}/H)(z - z^2/H)$. The solutions are derived from two total differential equations, together equivalent to Eq. (1), which describe the motion and development of individual M-packets. The solutions presented in the references are correct, and their development illuminates the physical processes involved; however, it seems desirable to present solutions developed from the formal logic customarily employed by mathematicians for such equations and within the historical context of the equations. This work has been done by Dr. E. A. Newburg and will be presented as part of a future scientific report.

1.4 A Generalized Model that Includes Cloud and Rain

In the earlier studies based on equations like (1), cloud is omitted; all the condensed water is assumed to exist as rain or snow falling at velocity V, constant at any one height.

During May, June, and July, 1962, we have generalized the earlier theory to include an elementary modeling of the bulk effects of cloud coalescence, collection of cloud by precipitation and evaporation of precipitation, and of the effects of these processes on the partitioning of water substance among precipitation, cloud, and water vapor. The following are the principal assumptions inherent in our preliminary mathematical formulation.

(1) Cloud is condensed water that has no appreciable fall speed relative to the air.

(2) Cloud forms in rising saturated air, and evaporates in saturated descending air at the rate $wG = -w(dQ_s/dz)$, where w is the vertical air velocity and Q_s is the saturation vapor density.

(3) Cloud changes to raindrops distributed in size according to the inverse exponential distribution of Marshall and Palmer [8] at the rate $K_1(m - a)$, where K_1 and a are constants and m is the cloud's water content. The term in Eqs. (2) and (3) that embodies this assumption is called the autoconversion term.

(4) Once rain is formed, it combines with cloud or evaporates in subsaturated air, in accordance with approximate forms of derived physical relationships. The terms in Eqs. (2) and (3) that account for these processes are the accretion of cloud term and the evaporation term, respectively.

(5) Although an inverse exponential distribution of precipitation particles is assumed for computing cloud collection and evaporation, the vertical mass transport of precipitation is based on the terminal fall speed of the drop whose diameter D_0 divides the distribution into parts of equal water content.

The new equations for vapor, cloud, and precipitation content include the macroscopic effects of cloud physics processes and incorporate the same principles of continuity discussed in the references. In an incompressible atmosphere, we have

$$\frac{\partial m}{\partial t} = -u\frac{\partial m}{\partial x} - v\frac{\partial m}{\partial y} - w\frac{\partial m}{\partial z} + wG - K_1(m - a) - K_2 E n_0^{0.125} m M^{0.875} - K_3 n_0^{0.35} m M^{0.65}, \quad (2)$$

$$\frac{\partial M}{\partial t} = -u\frac{\partial M}{\partial x} - v\frac{\partial M}{\partial y} - (w + V)\frac{\partial M}{\partial z} - M\frac{\partial V}{\partial z} + K_1(m - a) + K_2 E n_0^{0.125} m M^{0.875} + K_3 n_0^{0.35} m M^{0.65}, \quad (3)$$

where m may be positive, negative, or zero and is the cloud density plus the vapor density minus the saturation vapor density; $M > 0$ is the water content of precipitation; E, a number between 0 and 1, assumed independent of D, is the efficiency with which precipitation particles collect cloud; K_1 in the autoconversion of cloud term is of the order of 10^{-3} sec^{-1}; K_2 in the accretion of cloud term is 6.95×10^{-4} when $m > 0$ and is zero otherwise; K_3 in the evaporation of precipitation term is 1.35×10^{-6} when $m < 0$ and is zero otherwise; and V, the fall speed of precipitation, is given by $V = -38.6 n_0^{-0.125} M^{0.125}$ m/sec.

The number of precipitation particles per cubic meter of air per unit diameter interval is given by

$$n = n_0 e^{-\lambda D}, \quad (4)$$

where $\lambda = 3.75/D_0$ (Atlas [1]). The order of magnitude of n_0 is 10^7 m^{-4}.

1.5 Sample Derivation

As an example, the following outlines the derivation of the accretion term in Eqs. (2) and (3).

The rate at which volume is swept out by one drop of diameter D_i falling at a speed V_i is $-\pi D_i^2 V_i/4$ (where $V_i < 0$), and the rate of accumulation of cloud water

by a single precipitation particle is

$$\frac{\delta M_i}{\delta t} = - \frac{\pi D_i^2}{4} E_i V_i m, \tag{5}$$

where E_i is the efficiency of catch.

The rate of growth of the liquid water content in the entire distribution of precipitation particles is given by integrating Eq. (5) over all the particles; i.e.,

$$\frac{dM}{dt} = \int_0^\infty \frac{\delta M}{\delta t} n \, dD. \tag{6}$$

This integration is accomplished by substituting for V_i in Eq. (5) according to the relation $V = bD^{0.5}$, due to Spilhaus [9]. Then, with E independent of D, and with $b = -130D^{0.5}$ sec^{-1}, we have

$$\frac{dM}{dt} = \frac{130}{4} \pi E n_0 m \int_0^\infty D^{5/2} e^{-\lambda D} dD, \tag{7}$$

or

$$\frac{dM}{dt} = \frac{130}{4} \pi E n_0 m \frac{\Gamma(3.5)}{\lambda^{3.5}}. \tag{8}$$

Equation (9) describes the collection of cloud by precipitation and is obtained from Eq. (8) by substituting for λ its equivalent expression in terms of M:

$$\frac{dM}{dt} = 6.96 \times 10^{-4} E n_0^{0.125} m M^{0.875} \text{ gm m}^{-3} \text{ sec}^{-1}. \tag{9}$$

The derivations of the fall-speed equation in terms of n_0 and M and of the evaporation term involve integrals similar to that in Eq. (7). The evaporation term is based on a simple modeling of the evaporation functions of Kinzer and Gunn [6].

1.6 Method of Solution of Equations of the Generalized Model

It has been suggested that the most accurate solution of Eq. (1), with V constant for $M > 0$, is obtained by considering the motion and development of M along its streamlines, as described by the equivalent total-differential equations. This method

is discussed at length in the paper whose abstract appears in Section 1.2. Although such Lagrangian methods of solution were emphasized in the original proposal which this contract now supports, these methods do not appear feasible in connection with the solution of Eqs. (2) and (3) because the streamlines are not fixed as in the simpler problem and application of the method would involve too many difficult and lengthy computations.

We have, accordingly, turned again to finite-difference methods based on a rectangular grid. The computer program prepared by Mr. Gerald Wickham for the one-dimensional forms of Eqs. (2) and (3) follows a method first suggested by P. D. Lax [7]. We write Eqs. (2) and (3) in the form

$$\frac{\partial U}{\partial t} + \frac{\partial F}{\partial z} = B, \tag{10}$$

where U, F, and B are the vectors

$$U = \begin{bmatrix} M \\ m \end{bmatrix}, \quad F = \begin{bmatrix} (w + V)M \\ wm \end{bmatrix}, \quad B = \begin{bmatrix} B(M) \\ B(m) \end{bmatrix}, \tag{11}$$

and the B's are given by

$$B(M) = M \frac{\partial w}{\partial z} + \text{cloud physics terms}, \tag{12}$$

$$B(m) = m \frac{\partial w}{\partial z} + wG + \text{cloud physics terms}. \tag{13}$$

The finite-difference formulation is

$$U(z, t+k) = U_{av}(z, t) + \frac{k}{2h}\{F(z-h, t) - F(z+h, t) + h(1-\mu)[B(z+h) + B(z-h)] + 2h\mu B(z)\}, \tag{14}$$

where k is the time increment, h is the height increment, μ is an experimental weighting parameter in the range $0 \leq \mu \leq 1$, and

$$U_{av}(z, t) = \frac{1}{2}[U(z+h, t) + U(z-h, t)]. \tag{15}$$

At a lower boundary, we use

$$U(0, t+k) = U(0, t) + \frac{k}{h}[F(0, t) - F(h, t) + hB(0, t)], \tag{16}$$

where the F's and B's do not include terms involving w or $\partial w/\partial z$. The equations are solved under the mixed conditions

$$U(z, 0) = g_1(z) \qquad (0 \le z \le H),$$
$$M(H, t) = g_2(t) \qquad (0 \le t \le T). \tag{17}$$

The cloud physics terms in the B's have been modified slightly from the form given in Eqs. (2) and (3), so that their first derivatives are Lipshitzian [2]. The classical Courant-Friedrichs-Lewy stability criterion is observed in choosing the mesh: the domain of dependence of a point with respect to the differential equation always lies within the domain of dependence of this point with respect to the difference equation.

1.7 Sample Solution

First problems solved by the IBM 7090 computer included those simple one-dimensional cases discussed in the references, whose solutions are accurately known. In this progress report, we note merely that the computer answers are highly gratifying; the finite-difference scheme is distinctly superior to that used in the earlier work.

Figure 1 shows some of the results obtained from the first run of the computer on a problem that included conversion of cloud to precipitation and collection of cloud by precipitation. The solution demonstrates many features of a shower which appear analogous to events in the real atmosphere, although the input parameters for this first trial constituted a relatively incomplete simulation of the real tropical atmosphere. Further discussion of this and other solutions will be included in the next progress report.

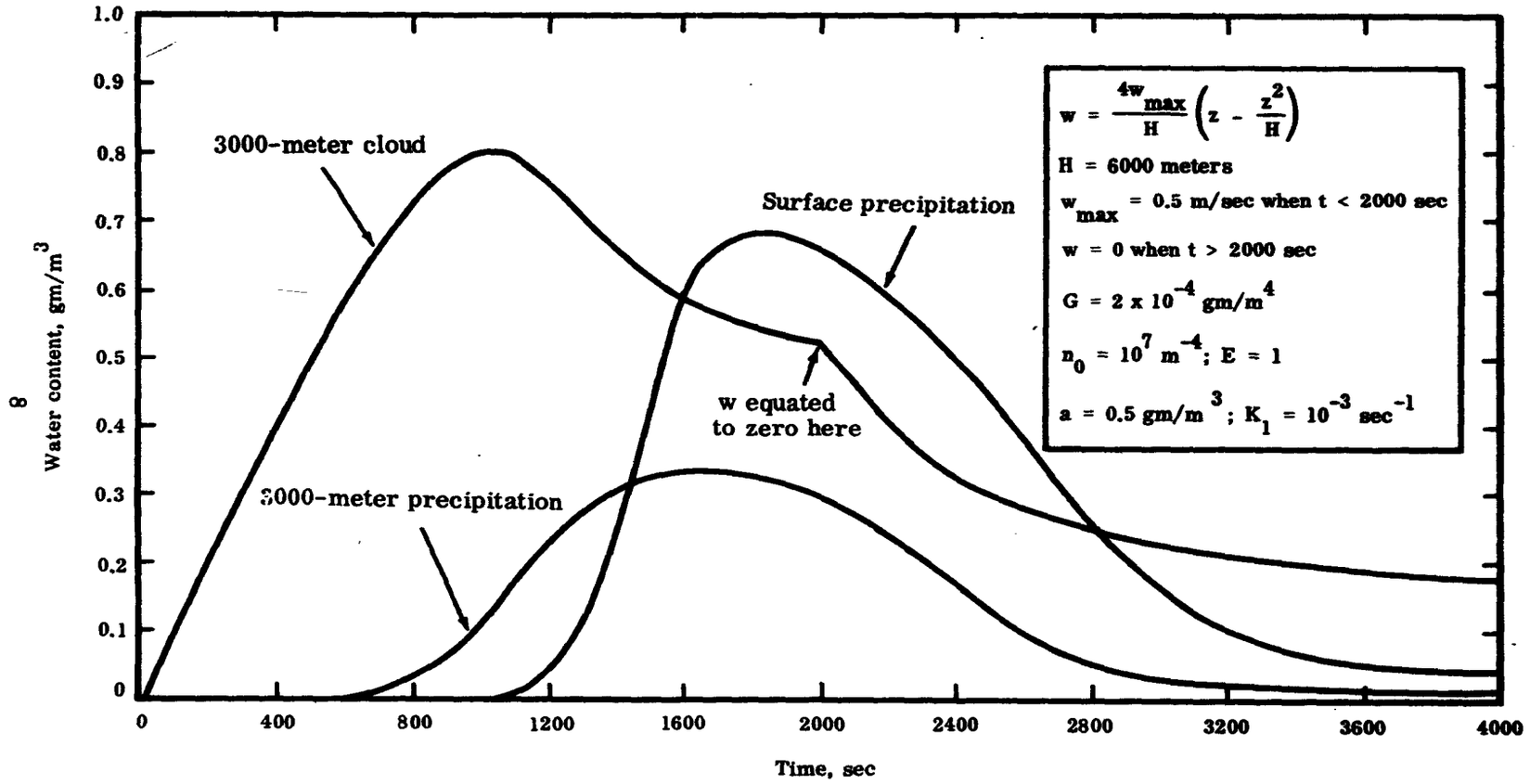

Fig. 1. Time dependence of the water content of cloud and precipitation at a height of 3000 meters at the center of an area where updrafts extend to 6000 meters. The variation of precipitation water content at the surface is also shown. The cloud water at the surface is always zero.

1.8 References

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2. Forsythe, G. E., and W. R. Wassow, Finite Difference Methods for Partial Differential Equations, p. 46. New York: John Wiley & Sons, (1960).

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6. Kinzer, G. D., and R. Gunn, "The Evaporation, Temperature, and Thermal Relaxation Time of Freely Falling Water Drops," J. Meteorol. 8:2, 71–83 (1951).

7. Lax, P. D., "Weak Solutions of Nonlinear Hyperbolic Equations and Their Numerical Computation," Communs. Pure and Appl. Math. 7:2, 159–193 (1954).

8. Marshall, J. S., and W. Palmer, "The Distribution of Raindrops with Size," J. Meteorol. 5:4, 165–166 (1948).

9. Spilhaus, A. F., "Raindrop Size, Shape, and Falling Speed," J. Meteorol. 5, 108–110 (1948).

2.0 CONCLUSIONS

The presently available one-dimensional computer program should contribute greatly to evaluation of the relationships between the developments of precipitation and the strengths of condensation, coalescence, accretion, and evaporation processes. The analysis of one-dimensional solutions should be vigorously pursued.

The study of budget parameters will require computer programs to solve the continuity equations in two and three dimensions [3, 4].

3.0 PROGRAM FOR NEXT INTERVAL

Theoretical and numerical approaches will be used to study solutions of the one-dimensional equations. Among the many questions to be addressed are:

(1) Under what conditions, if any, are steady updrafts and cloud physics parameters associated with oscillatory behavior of the cloud and precipitation distributions?

(2) How is the time of onset of precipitation related to the strengths of the coalescence and accretion processes? How do variations of these processes affect the peak rate of rainfall and its rise time?

(3) How do the rate and duration of surface rainfall vary with the strength and duration of the updrafts?

(4) How do the several variables relate to the persistence of cloud aloft?

(5) Can the shape and intensity of the wind field be deduced from observations of the cloud and precipitation distributions?

4.0 IDENTIFICATION OF PERSONNEL

4.1 Extent of Participation

Name	Title	Total hours worked during the quarter (approximate)
E. Kessler	Principal Investigator	135
E. A. Newburg	Mathematician	75
G. Wickham	Programmer	65
P. Duchow	Senior Research Aide	80

Secretarial, administrative, and drafting assistance was also provided.

4.2 Biographies of Key Personnel

Edwin Kessler, III, Sc. D. Dr. Kessler is Director of the Atmospheric Physics Division of the Atmospheric and Oceanographic Sciences Department. He joined the Research Center in 1961 as senior research scientist in the Environmental Meteorology Division, and was subsequently named manager of the Radar Meteorology Section. He moved to his present position early in 1962.

Prior to his joining the Research Center staff, Dr. Kessler was Chief, Synoptic Meteorology Section, Weather Radar Branch, Geophysics Research Directorate, Bedford, Mass. In this post, Dr. Kessler did extensive research into the interpretation of weather-radar data in terms of atmospheric fields of motion, water content, and temperature, and into the data's application to weather forecasting. He invented an instrument which facilitates accurate measurement of radar reflectivity distributions. Dr. Kessler also monitored the GRD contractual program in radar-synoptic meteorology.

Dr. Kessler has been a teaching and research assistant at M.I.T., a visiting lecturer in climatology at Boston University, and has consulted with the Lincoln Laboratory concerning the relation of meteorological parameters to tropospheric scatter propagation. More recently, he has been a guest lecturer at the University of Miami (Fla.) and at M.I.T.

Edward A. Newburg, Ph.D. Dr. Newburg is a Research Scientist in the Atmospheric and Oceanographic Sciences Department. He is responsible for the analysis of mathematical problems that originate in the various Departments of the Research Center and for the initiation of research in mathematical problems relevant to all areas of the environmental sciences.

From 1958 to 1961, Dr. Newburg was a mathematician in the Nuclear Division of Combustion Engineering, Inc. His work there included formulation of mathematical models for the physical description of neutron chain reactors. Much of his effort was devoted to the numerical solution and qualitative analysis of equations describing the kinetics and dynamics of power reactor systems.

Since 1960, Dr. Newburg has been an adjunct assistant professor of mathematics at the Hartford Graduate Division of Rensselaer Polytechnic Institute. Before 1958, he was a part-time teaching assistant in the mathematics departments of the University of Illinois and Purdue University. During the summers of 1953, '54, '55, and '57, he was employed by the Allison Division of General Motors Corp., where his highest position was project engineer.

Gerald C. Wickham, M.A. Mr. Wickham is a Research Associate in the Mathematical Services Division. He is responsible for the design and programming of engineering and scientific problems for large-scale digital computers.

Except for a short period of graduate study in 1959 and 1960, Mr. Wickham was engaged in the teaching of mathematics from 1954 through 1961. Prior to that time he was employed as an assistant engineer with the Aircraft Gas Turbine Division of General Electric Corp.

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1st Quart. Progress Rpt., May 1, 1962–July 31, 1962. 16 pp. incl. 1 fig. Contract DA 36-039 SC 89099. DA Proj. 3A99-27-005. UNCLASSIFIED report.

During May, June, and July, 1962, previously unpublished material was collected, organized, and submitted to the Monthly Weather Review under the title "Elementary Theory of Associations between Atmospheric Motions and Distributions of Water Content."

Also, a theory of the relationships among cloud, precipitation, vapor, and air motions, which includes a quantitative modeling of the bulk effects of many processes of cloud and precipitation physics, was completed. The theory is formulated in two continuity equations that describe the development of vapor, cloud, and precipitation distributions when initial and boundary conditions and the wind field are prescribed.

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